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A Review of Fault Monitoring for Utility-scale Solar Arrays

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ABSTRACT

As the solar energy output of the Caribbean grows, so does its need for proper maintenance of such systems. Solar modules degrade with time, and with this degradation comes a loss in their electrical performance. Solar module performance is also affected by common problems such as: manufacturer defects, adverse weather, and accidental damage. Thus, in order for a PV plant to maintain its capacity factor, the plant personnel must regularly inspect and maintain the array to ensure that anything detrimental to their performance is identified and rectified. This paper seeks to provide insight into the maintenance and inspection processes used by local and regional photovoltaic (PV) operators. These insights include the current methods that local PV operators use for fault inspection and maintenance. The effectiveness of these methods will be investigated and the way these methods could be improved will be explored. The inspection and maintenance techniques will also be compared to the current global standards, to determine whether local PV projects are operating competitively in an international context. Additionally, this paper will explore current trends and innovative methods of inspection, such as thermographic imaging for fault detection and the use Unmanned Aerial Systems (UAS) for automated/semi-automated inspection. The cost-effectiveness and value proposition these innovative systems have to offer will also be analyzed to empirically determine what local PV operators stand to gain if these systems were developed and adopted.

INTRODUCTION

Large-scale photovoltaic (PV) plants consist of an array of thousands of modules for smaller farms or hundreds of thousands for larger plants. For example, Content Solar, Jamaica's first and only utility-scale solar farm has around 91,000 modules and produces 20 MW of power **[1]**. This makes it one of the largest solar farms in the Caribbean, however, globally, this is on the smaller side of the spectrum. One of the largest single-site solar project in the world has over 2 million modules **[2]**. For a PV plant to maintain a high capacity factor, maintenance is paramount. However, proper maintenance is difficult partly due to the vast number of modules that must be individually inspected to ensure that each is operating as it should. There are also several complications with PV maintenance as the modules are relatively vulnerable. The semiconductor material of the solar cells degrades over time, electrical faults, internal or external to the module, can cause moderate to severe damage to the modules themselves, and they are susceptible to a variety of environmental impacts: soiling due to dirt in the wind and local animals (e.g. birds), expansion and contraction due to changing temperatures, and impacts from stray projectiles (e.g. stones from mowing grass, debris in high winds) **[3]**.

PV array maintenance is difficult, and time consuming for very large arrays, but it is a repetitive task, thus automation can be a great boon to the issue of maintenance. This paper aims to highlight the ways in which automation can help streamline the PV maintenance process by reducing the overhead required for the operation. There are several new, as well as, upcoming utility-scale PV projects in the Caribbean that can benefit from such systems. Some of these plants are listed below in Table 1 [1] [4] [5].

Table 1: List of some major Utility Scale PV Projects in the Caribbean (Source: [1] [4] [5])

Plant	Country	Current Installed Capacity	Year / Expected Year of Commission
Monte Plata	Dominican Republic	60	2016
Paradise Park	Jamaica	51	2019
Conten Solar	Jamaica	20	2016
LUCELEC Solar Farm	Jamaica	3	2018

PV Module Faults

As stated previously, utility-scale PV arrays have vast amounts of modules. The large number of modules means there are many possible points of failure, i.e. system faults, associated with the arrays of the solar modules. Additionally, solar modules consist of several solar cells connected in series. Thus, a fault in just one cell can have a domino effect, impacting the power produced by the module by affecting the entire string of cells.

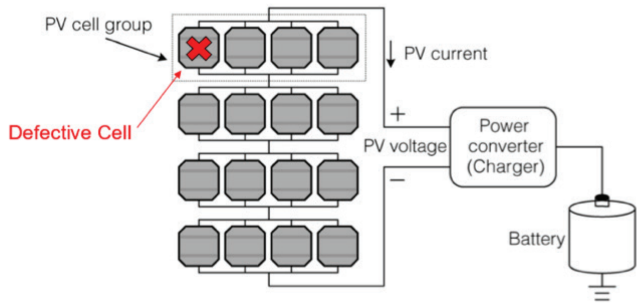

Figure 1: Schematic PV Module System Diagram with a defective cell.

Even though only one cell in the cell array of 16 is defective, the total power output of the array can be reduced. This is because the system cannot perform optimally while a cell is defective. This emphasizes the vulnerability of PV modules to power output reduction due to faults.

PV arrays are comprised of PV modules. These modules are connected in series-parallel arrangements to optimize their power output, to provide energy to the grid. Each of these modules are a part of a string, and each of the modules is subject to faults. A PV module fault is defined as any failure or defect that affects the performance of the module. Faults can affect every part of the module or the array, so they can be categorized as such: semiconductor material, encapsulation, internal wiring, frame and mounting faults [6]. Some typical faults that occur in PV modules are laid out in Table 2.

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Table 2: Typical PV Module Faults. (Rycroft 2016)

Fault Type	Observation	Current Installed Capacity
Semiconductor Material	Cracks in semi-conductor material, snail trails, etc.	These types of faults are generally due to a breakdown in the semi-conductor material that constitutes the PV cell.
Paradise Park	Discoloured or opaque cells	Degradation of the encapsulant
Internal Wiring	Broken or burned bus bars	Cell/module over current

2.1 Fault Detection

System faults directly affect the efficiency of the plant, and as such affect power output and thus the profitability of the plant. System maintenance is important and on-site engineers are required to detect faults and address maintenance issues. Faults can be detected using a SCADA (Supervisory Control and Data Acquisition) system, as these systems monitor the power output at various stages throughout in electricity generation and transmission sections of the plant [7]. SCADA systems, however, are generally not suited for detecting faults on the smaller scale i.e. on the module to module level. For these minor faults to be detected, the individual modules must be investigated.

2.2 Thermographic Imaging

Thermographic imaging of the modules is sometimes used to individually investigate the modules in order to detect faults. This is because most solar module faults affect the current flow through cells/modules. An increase in current flow, causes more heat to be generated, and thus the anomaly can be seen clearly through thermographic imaging. This is what makes thermographic imaging so effective for solar module fault detection. A fault that is undetectable by regular imaging becomes easily seen by thermographic imaging.

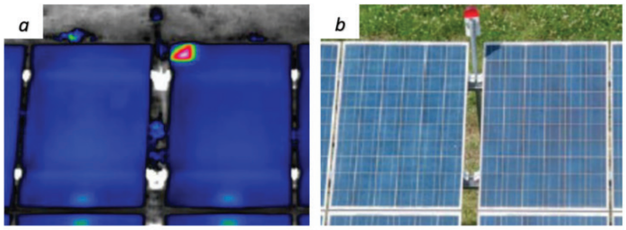

Figure 2: Representation of solar modules using a) a thermographic image of a partially shaded module and b) an image of a partially shaded module (upper left-hand corner). Adapted from VATH (2016).[8]

Figure 2 shows a comparison between a regular image of a shaded module and the thermographic equivalent. What looks like very minor shading in the regular image, is seen as a very bright hotspot in the thermographic image.

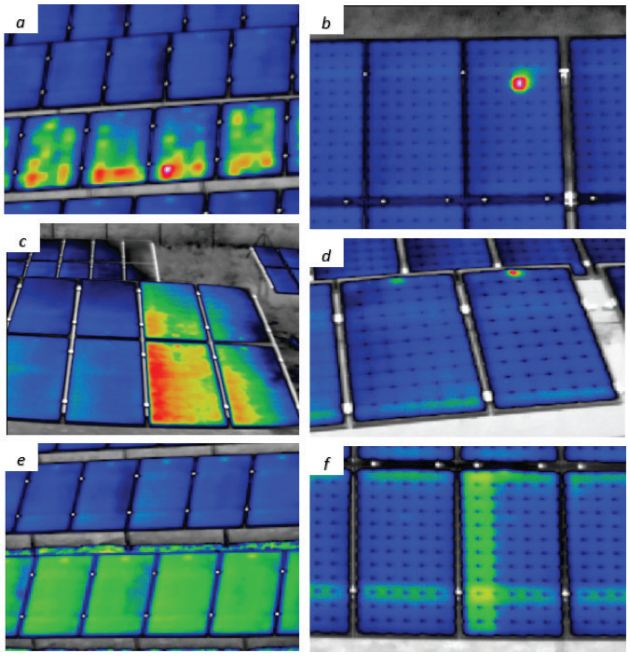

Figure 3: Collage of common solar module faults showing a) short circuited modules, b) an overheated cell, c) reversed polarity connectors, d) an overheated junction box, e) several modules in 'idle mode', and f) a module with a bypassed substring. Adapted from VATh (2016).

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As seen from Figure 3, the pattern observed from thermographic imaging of faulty modules can be used to determine the nature of the fault. For example, in Figure 3b, the hotspot on the overheating cell is immediately visible. Similarly, in Figure 3d, a hotspot can be seen at the top middle of the module (typically where the junction box is), thus a possible inference is that the junction box is overheating. In Figure 3e, an entire string of modules is idle. Idle meaning the modules are open circuited, i.e. they are not connected to a load. This indicates a connection issue and means the string of modules is not producing any usable energy. This kind of fault would be very serious for any solar array, because of the significant power loss, and is undetectable by regular imaging.

2.3 Fault Detection using Aerial Thermography

An aerial view of a PV array allows the viewer to see many modules simultaneously, much more compared to a ground view. Thus, an aerial view is much more advantageous for inspection purposes. Muntwyler et al. (2015) [9] demonstrated how simple it is to attach cameras (thermal and regular for comparison shots) to a drone and fly over an array. This solution is far more convenient than having on-site personnel manually inspect each individual module as the aerial view allows the operator to see many modules at once.

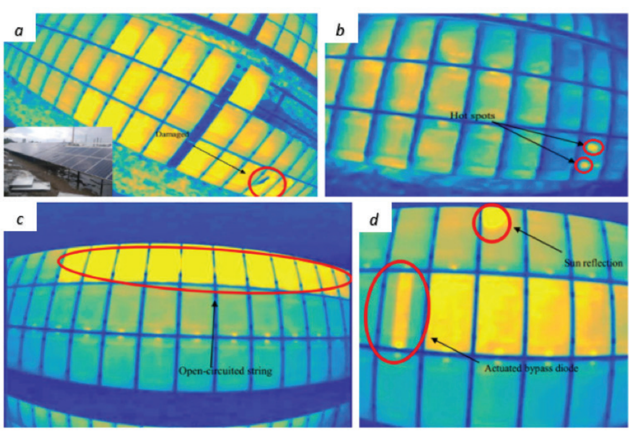

Figure 4: Aerial thermographic images of: a) highlighted damaged module. b) identified module hot spots. c) open circuited string. d) actuated bypass diode and sun reflection. Adapted from Aghaei et al. (2018)[10].

Aghaei et al. (2018) [10], demonstrated the effectiveness of a remote-controlled PV monitoring drone after severe weather conditions, specifically a meteorological tsunami. The thermal images captured by the thermal camera mounted to the drone, were taken in grayscale, and then coloured to aid in the visualization of the faults. The drone operator was able to detect hot spots, defective bypass diodes, and shorted and open circuit strings. These faults, gone undetected, greatly reduce the power output of the plant, hence being able to spot them is a great advantage.

There are other methods of aerial PV inspection as well. PV maintenance companies like Heliolytics, have developed an aircraft mounted sensor package that can be used to get very high-quality, large scale, thermographic images of PV arrays. They also use their own analysis algorithms to detect and diagnose faults in the array.

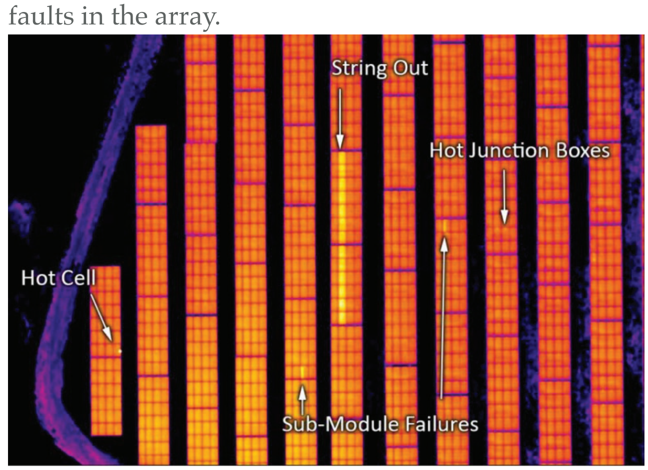

Figure 5: High-resolution infrared aerial imaging of failed strings, modules, and cells

Similar to the smaller scale images in Figure 3, the general thermographic pattern of the faults in Figure 4 allows the operator to diagnose the problems with the modules [3]. The Heliolytics system has the clear advantage of being able to see extremely large sections of the array at once. In Figure 3, the UAS based system could see 30+ modules at a time, whereas the Heliolytics can see upwards of 1,000 modules in a single image.

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Conclusion

Currently, in the Caribbean, these aerial thermography methods have not been fully implemented. At Content Solar (Clarendon, Jamaica), for example, they use thermography to detect faults. However, the thermographic inspection is done manually by service engineers, on foot. Thus, the inspection process is man-hour intensive (as they have close to 100,000 modules), and as such is not performed as frequently as it should be. Content Solar, and indeed many other solar plants in Jamaica and the wider Caribbean could greatly benefit from aerial thermography. Especially an automated version of such a system. However, there are a variety of factors that may be influencing the lack of use of aerial thermography. These factors could include:

Availability of the technology: While such systems are being used in developed nations, the Caribbean, has limited access to the skills and materials necessary for this technology.

Cost: A lot of the technology used in thermography is proprietary, therefore there is a significant barrier to entry in developing and using these technologies.

Lack of knowledge: Solar operators could be unaware of the technologies used in thermography/aerial fault detection.

It is difficult to determine which of these factors most inhibits the use of aerial thermography, as it is entirely dependent on the specifics of each array and their operators. Therefore, further research could be done into why these systems are not in use in the Caribbean. Nevertheless, as the number utility-scale PV arrays in the Caribbean increases, so does the need for proper maintenance on these systems.

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